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An Attractive Small Tandem Mirror Fusion Reactor

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MINIMARS: AN ATTRACTIVE SMALL TANDEM MIRROR FUSION REACTOR*

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Abstract

Through the innovative design of a novel end plug scheme employing octopole MHD stabilization, we present the conceptual design of "MINIMARS", a small commercial fusion reactor based on the tandem mirror principle. The current baseline for MINIMARS has a net electric output of 600 MWe and we have configured the design for short construction times, factory-built modules, inherently safe blanket systems, and multiplexing in station sizes of ~ 600-2400 MWe. We demonstrate that the compact octopole end cell provides a number of advantages over the more conventional quadrupole (yin-yang) end cell encountered in the MARS tandem mirror reactor study [1], and enables ignition to be achieved with much shorter central cell lengths. Accordingly, being economic in small sizes, MINIMARS provides an attractive alternative to the more conventional larger conceptual fusion reactors encountered to date, and would contribute significantly to the lowering of utility financial risk in a developing fusion economy.

Introduction

The Mirror Advanced Reactor Study (MARS) completed in FY83 [1] and the forerunner of the current MINIMARS study, employed a quadrupole end cell in the form of a complex double yin-yang magnet set with additional transition coils. While quadrupole end cells provide a well tested method of MHD stabilization, they have two major disadvantages in terms of reactor attractiveness:

- o Because of the requirements of balancing the geodesic curvature of the non-axisymmetric fields, we require a double quadrupole system resulting in a large, complex and expensive magnet set with a requirement for many tens of megawatts of ECRH power.

- o Because of the possibility of trapped-particle modes, the quadrupole end cell must be configured with an "outboard plug" (i.e., confining potential outboard of the MHD anchor) resulting in a large plasma volume for trapping of passing ions. This results in a corresponding requirement for a long central cell length to obtain ignition of the fusion plasma.

Accordingly, in FY85-86, Lawrence Livermore National Laboratory, in a partnership with the Fusion Engineering Design Center, the University of Wisconsin, TRW, General Dynamics/Convair, Grumman Aerospace Corporation, Bechtel, Ontario Hydro and Argonne National Laboratory is undertaking the conceptual design of MINIMARS, a small commercial fusion reactor with compact octopole end plugs. In contrast to the MARS double quadrupole, the MINIMARS octopole configuration produces an essentially axisymmetric end cell core plasma. The resulting short, compact end cells enable ignition to be achieved with much shorter central cell lengths and considerably improve the economy of scale characteristics for small (250-600 MWe) reactors. In particular MINIMARS achieves a greater Q than MARS, in a reactor of half the power!

We have adopted four basic objectives for the study:

- o Design and engineer an attractive point reactor design with octopole plugs at 600 MWe.

- o Assess growth systems cost of electricity, total capital investment (i.e., utility financial risk) and economy of scale for MINIMARS reactors in the range ~ 250-1200 MWe. Investigate, in parallel, the benefits of multiplexing small (250-600 MWe) MINIMARS reactors in large (1200-2400 MWe) station sizes.

- o Configure the design for low radioactive afterheat and inherent/passive safety under LOCA/LOFA conditions, thereby obviating the requirement for complex and expensive active engineered safety systems.

- o Investigate other novel MHD stabilization schemes in addition to the octopole (e.g., wall stabilization, RF stabilization, etc.) and evaluate reactor potentials.

Plasma Engineering

Fig. 1 shows a cross-section of the MINIMARS reactor, while Table 1 lists the principal parameters of the current design (as of Nov. 1985). Fig. 2 shows a detail of the end cell octopole magnet assembly.

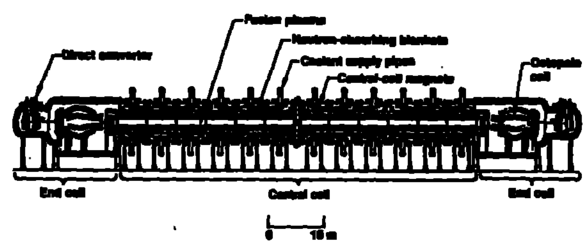

Fig. 1. The MINIMARS Tandem Mirror Reactor (Interim Design).

With the important exception of MHD and radial transport, the physics basis of the core plasma in MINIMARS is similar in principle to previous thermal-barrier tandem-mirror machines (e.g., see Ref. 1).

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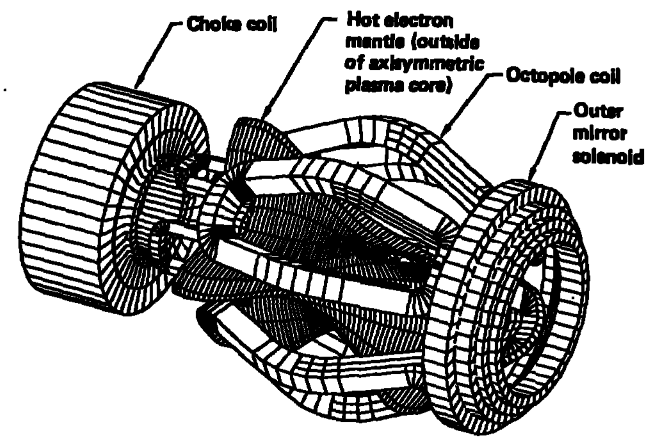

Fig. 2. The end cell magnet assembly showing the discrete octopole coil and the hot electron mantle.

Radial pressure of the reacting deuterium-tritium (DT) fuel ions in the 82-m long central cell is contained by the 2.7 T solenoidal field, whereas the axial pressure is contained mainly by the high-field (24 T) choke coils at each end. Nearly all the 3.5 MeV fusion alpha particles are born mirror trapped in the central cell. A small fraction (< 10%) of the central cell ions pitch angle scatter into the loss cone, pass into the octopole end cell and reflect off the positive plugging potential, thus returning through the central cell. The magnitude of the potential peak (132 kV relative to the central cell potential) reduces the central-cell ion end loss sufficiently to allow fusion alpha heating to sustain residual central-cell energy losses that mainly result from end-cell ion trapping. Therefore, the central cell is ignited relative to losses from the central cell volume.

Table 1. MINIMARS Parameters (Nov. 1985)

General	
Net electric power (MWe)	600
Fusion power (MW)	1219
Neutron wall loading (MW/m^2)	2.70
Q	38.5
Recirculating power fraction	0.187
COE (mills/kWhr)†	~36.1
Central Cell	
Length (m)	82
Plasma radius (m)	0.5
B-field (T)	2.67
$\langle\beta\rangle$	0.6
End Cell	
Choke coil field (T)	26
Minimum plug field (T)	1.98
$\langle\beta\rangle$	0.17
Neutral beam power* (MW)	7.76
ECRH power (MW)*	31.8

*injected - both ends.

†Levelized, 1985$, zero inflation and escalation.

An intervening "thermal barrier" is required in the end cell to moderate electron heat conduction from the potential peak and, therefore, to reduce end cell electron cyclotron resonant heating (ECRH) power. A depression in the end cell ion density is formed by microstable sloshing ions fueled at each end by a 340 kV negative ion neutral beam source. Mirror-trapped hot electrons sustained by ECRH heating at the midplane of the sloshing ion distribution provide the negative potential (-126 kV relative to the central cell) required for the thermal barrier. Thus, to summarize, ions are confined axially by the 132 kV positive potential in the end cell, electrons are confined axially by the potential difference between the end wall and the central cell (-146 kV), while central cell electrons are prevented from "communicating" with the end cell potential peak by the intervening potential dip at -126 kV.

MHD stability of MINIMARS is obtained by means of the octopole coil and the hot electron mantle (Fig. 2). Unlike the quadrupole (yin-yang) magnetic field, the octopole field is characterized by a minimum-B region which occurs at a radial distance off the central axis and outside the end cell core plasma. Since our core plasma, mapping from the central cell, has a quartic pressure profile, it would be impossible to satisfy the conditions for flute interchange stability for the core alone, because the bad field curvature drive of the central cell and end cell is always favored over the good curvature regions under the mirror coils. Accordingly, we arrange for the region in the end cell between the core plasma and the minimum-B octopole field to be filled by a mantle of hot mirror-confined electrons sustained by a separate ECRH system. The added plasma pressure forms a sufficiently large positive pressure gradient out to the minimum-B point to ensure that the mantle, of limited axial extent, satisfies the flute interchange stability criterion along the entire flux tube. Fuller consideration to MHD stabilization can be found in Refs. 2 and 3.

Passing cell ions which undergo collisional trapping in the end cell between the potential peak and the choke coil magnetic field peak must be removed (or "pumped") at the rate at which they trap, otherwise the end cell would fill with trapped ions and the thermal barrier would be destroyed. To provide this pumping, we configure "drift-pump" antennas in the end cell under the octopole coils which, by means of an induced ponderomotive potential, effect a resonance between the coil frequency and the drift frequency of the trapped ions (further details may be found in Ref. 2). The induced radial transport of these trapped ions constitute the dominant energy loss channel from the central cell. Consequently, for the central cell plasma to remain ignited, the central cell must be of sufficient length such that energy deposited by the energetic alpha particles in the central cell makes good the energy loss due to the pumping of trapped ions in the end cell.

Here then lies the problem with end cell magnetic configurations such as the MARS quadrupoles which have long characteristic lengths. A long end cell length requires a long central cell for ignition making it impossible to achieve small reactor sizes in an economic fashion. By contrast, the octopole provides a method of obtaining a short end cell configuration with a minimum end cell length (~ 8 m) determined only by sloshing ion adiabaticity, thus allowing us to consider economic tandem mirror reactors as small as 250 MWe. We illustrate this principle in Fig. 3, where the octopole end cell magnet set for MINIMARS (600 MWe) is compared with the quadrupole set for MARS (1200 MWe).

Clearly, for the plasma to remain neutral, the total current of ions leaving the machine must equal the electron loss current. Accordingly, because of the large positive plugging potential in the end cell, most of the ions diffuse radially through drift pumping to the edge of the core plasma where they penetrate the radially decreasing confining potential and then flow axially to the grounded halo scraper at the ends of the machine. Electrons, by contrast, flow axially and provide electricity by direct conversion (see below).

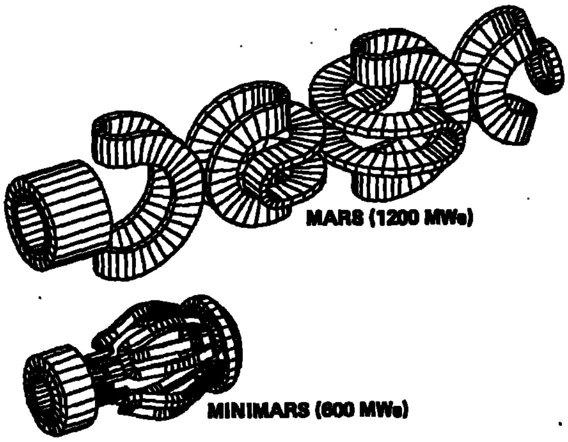

Fig. 3. A comparison of the end cell magnet sets for MARS and MINIMARS. The attractiveness of the octopole plug concept is clearly evident.

The Tandem Mirror Systems Code

As with all previous reactor studies, we began the MINIMARS project with a large, complex, plasma engineering design space, with a primary goal to ascertain the "best" machine design. With 44 system variables describing the plasma engineering design of the machine, we faced a potentially tedious and exhausting task of selecting (limited) areas of parameter space for single point analysis. Accordingly, we developed a new sophisticated code--the Tandem Mirror Optimization Systems Code [4]—which performs constrained non-linear optimization of the MINIMARS system design. The code operates by optimizing a user-specified figure-of-merit (e.g., cost of electricity) by variation of up to 44 systems variables (e.g., B-fields, lengths, temperatures, etc.) subject to a set of user-specified constraints (e.g., fixed net electric power, etc.). The systems code can now select in a single run (~ 15 minutes of Cray CPU time), a complete set of optimized plasma engineering parameters for a required reactor configuration, a task which formerly occupied months of parametric analyses with a single point code.

Blanket Design and Inherent Safety

In the area of blanket engineering, four separate candidate blankets were designed for MINIMARS. Each blanket was configured independently by a separate "advocacy" group. Each was required to satisfy the constraint of inherent safety (see below). The features of the four blankets are given in Table 2.

An interesting feature of the blanket studies was a comparison of the four in terms of economic ranking by use of the Tandem Mirror Optimization Systems Code (see above). Blanket-dependent input to the code included energy multiplication (M), thermal cycle efficiency (η_{th}), radial dimensions, unit costs of materials and maximum allowed wall loading for inherent safety (see below). Table 2 shows the

Table 2. The Four Candidate Blanket Designs for MINIMARS

	1	2	3	4
Participating Group	ANL	LLNL	UW	TRW
Coolant	Flibe	He	He	He
Breeder/ Multiplier	Flibe	Flibe/Be	LiPb/Be	Li/Be
Structure	Va-alloy	Va-alloy	HT-9	Va-alloy
TBR	1.18	1.053	1.069	1.104
Energy Multiplication M	1.28	1.80	1.47	1.66
Thermal cycle efficiency η_{th}	0.482	0.447	0.417	0.455
$M\eta_{th}$	0.62	0.80	0.61	0.76
COE (mills/kWhr)	34.9	42.5	35.9	52.3

resulting cost of electricity (COE). It is interesting to note from the table that although blankets 2 and 4 have a product of M times η_{th} which is 31% and 25% higher, respectively, than either blankets 1 and 3, the latter are clearly superior from an economic standpoint. This was due to the significantly higher unit costs of the high performance blankets. This would imply that fusion component costs have decreased to the point where high-performance, high-cost blankets may not be required. Blankets 1 and 3 were selected for further study in FY86.

With the present emphasis on inherent safety in fission plants, we believe that there is a strong incentive for designing MINIMARS with this attribute. An opposing argument which is often made is that reactor power density (or neutron wall loading) must be reduced to achieve inherent safety, thus increasing the cost of the fusion island. However, we maintain that the cost savings realized through both the elimination of expensive active engineered safety systems and the construction of the plant to less stringent regulatory standards more than offsets a large fusion core size [5]. Accordingly, we have adopted inherent safety as a design standard in MINIMARS. In this regard, under all credible accident conditions, we require the protection of the plant capital investment and limitation of radioactivity release with Federal guidelines, by systems which rely only on inherent properties of matter (e.g., thermal conductivity, specific heat, etc.) and without the use of active safety equipment.

Fig. 4 illustrates the attainment of inherent safety for blanket number 1 from Table 2. In the figure we show the maximum blanket temperature after shutdown as a function of neutron wall loading during operation for a loss-of-coolant-accident (LOCA) situation, when only the passive-inherent features of the blanket (i.e., thermal conduction and radiation) are utilized to limit the temperature rise due to radioactive afterheat. We have determined that the LOCA is the worst-case accident for this type of blanket. Note that providing we limit the incident wall loading during normal operation to less than about 5 MW/m^2, the maximum temperature rise under LOCA will be less than ~ 1200°C. This is the maximum allowable temperature for the vanadium-alloy blanket before permanent damage occurs. From Table 1, we see that the current baseline operates at a wall loading of 2.7 MW/m^2, i.e., well within the margin of inherent safety for this blanket.

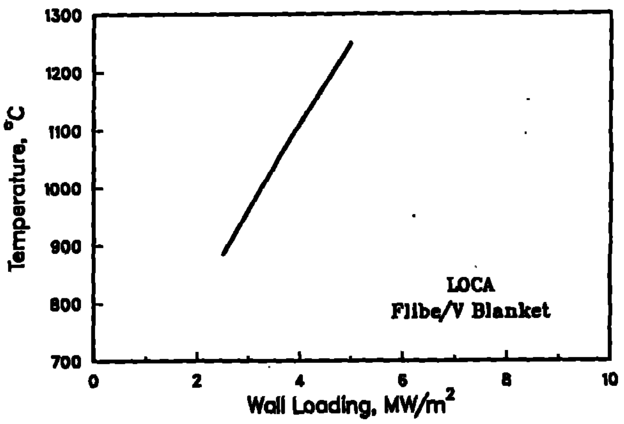

Fig. 4. Maximum temperature attained by the Flibe/Va-alloy blanket following a LOCA excursion as a function of operational wall loading. This blanket is inherently safe if operated below a wall loading of ~ 5 MW/m^2.

Configuration

The MINIMARS fusion power core (Fig. 1) is ~ 145 m long, ~ 93 m in diameter along its principal length and has a centerline height of ~ 9 m above the floor. The reactor is assembled from 24 central cell blanket modules, two end cell octopole magnet assemblies and two outer direct converter assemblies. The central cell modules are individually supported by piers and are linked to an integral fueling sector. A rigid cylindrical structure forms the vacuum boundary for the end cell and direct convertor assemblies and provides mounting hardware for the plasma heating systems.

A cross-section of the end cell configuration is shown in Fig. 5. The 26 T choke coil consists of an outer superconducting coil (~ 18 T) and a normal conducting insert coil (~ 8 T). The large octopole magnet (see also Fig. 2) is composed of four separate "window-frame" coils for ease of construction and maintenance. In addition, the end cell has provisions for negative ion neutral beams (3.9 MW injected each end), ECRH

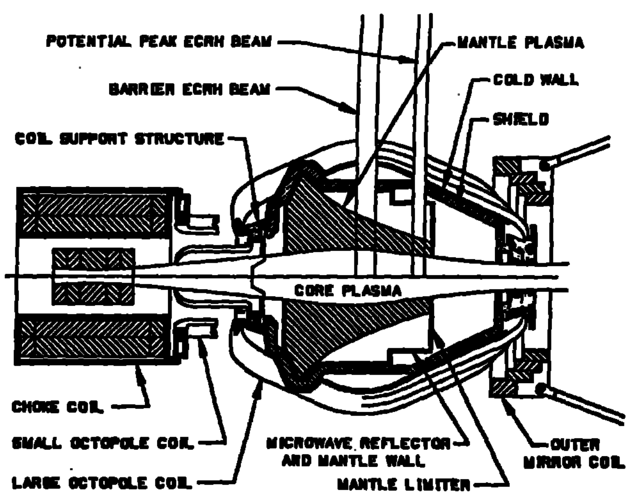

Fig. 5. Integration of the end cell subsystems.

systems (15.9 MW injected each end), microwave reflectors and drift pump coils. Clearly, our innovative designs for compact end cells have resulted in new requirements for equally innovative solutions to the integration of the auxiliary systems! Further details on the engineering configuration are given in Refs. 6-7.

Halo Pump and Direct Converter

The power available at the direct converter assembly is ~ 20% of the fusion power plus the injected heating power and we can convert this to electricity with an overall efficiency of ~ 0.68. The assembly is segmented radially into an inner (true) "direct converter" region and two outer grounded regions, the halo "scraper" and halo "dump", both utilized for thermal conversion. As outlined above, the dominant central cell ion loss is radial-induced diffusion through drift pumping in the end cells to the edge of the core plasma where they flow axially to the grounded halo scrapers. By contrast, the electron radial loss is small so that virtually all of the electron-loss current flows axially to the end wall, which is biased at -158 kV relative to the central cell. Accordingly, direct electrical power is available from the electron channel from the direct converters, whereas only thermally converted power is available from the ion-loss channel to the grounded halo scrapers that coaxially surround the direct converters.

The core plasma throughout the machine is surrounded by a halo plasma. This halo is deliberately enhanced by recycling most of the ions at the halo dumps to provide a shield around the core plasma to protect against gas and impurities. To act as a shield, the halo density must be about 5 x 10^{12} cm^{-3} and the electron temperature must be above 30 eV. These values ensure that the mean free paths for ionization of any impurity will be much shorter than the thickness of the halo. Impurities coming from the walls, vacuum leaks, or sputtering are ionized in the halo plasma and then flow along the magnetic-field lines to the grounded halo dumps situated radially outside the halo scrapers at the ends of the machine. This power is also thermally converted in MINIMARS by coupling the He coolant to the main steam generators. Table 3 summarizes the power available at the end wall.

Table 3. Energy Available at the End Walls

Element	Incident Power (MW)	Electrical Power (MWe)
Direct converter	164	105.8 (direct) + 24.2 (via thermal)
Halo scraper	14.1	5.9 (via thermal)
Halo dump	53.2	22.2 (via thermal)

Direct converter net efficiency = 0.65

Total end cell conversion efficiency = 0.68

Conclusion

At this stage in the MINIMARS project, we have configured a compact attractive fusion reactor which is in keeping with present utility desires for smaller, safer, lower-capital-investment power plants. It is, in particular, a significant advancement over the previous tandem mirror reactor design - MARS, especially in terms of improvement in economy of scale at smaller power levels. Based on engineering designs and estimates made so far, we believe that MINIMARS will achieve our cost of electricity target of < 40 mills/kWhr and should display a mass power density in the vicinity of 100 kWe/tonne. In conclusion, we should stress that MINIMARS is a multidisciplinary, multi-team effort of industry, university and national laboratory; the enthusiasm shown by these various contributors to the project and their collective expertise are the driving force for the project's rapid progress towards its ambitious goals.

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